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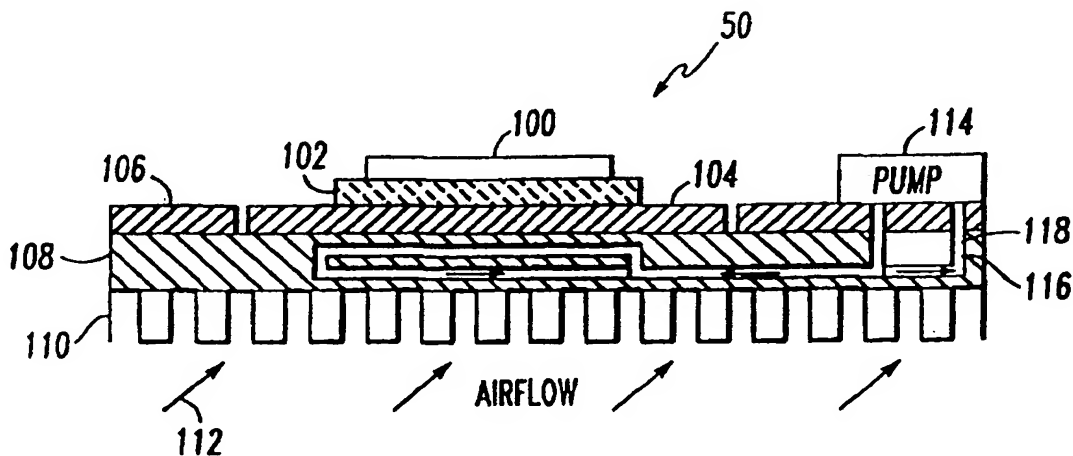(81) Designated States: JP, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

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(54) Title: NON-MECHANICAL MAGNETIC PUMP FOR LIQUID COOLING

(57) Abstract

A liquid cooling system contained completely on a circuit board assembly. The liquid cooling system uses microchannels etched within the circuit board, these microchannels being filled with electrically conductive fluid that is pumped by a non-mechanical, magnetic pump. The pump can be separate from the device on the circuit board which is to be cooled or it can be integrated with the device that is to be cooled. In the latter circumstance, the same current which flows through the electronic device is the current which generates the Lorentz force that pumps the electrically conductive fluid through the microchannel.

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NON-MECHANICAL MAGNETIC PUMP FOR LIQUID COOLING

Cross Reference to Related Applications

This application is related to copending U.S. patent application Serial No. 08/681,207 (WE58,813) entitled, "Microchannel Cooling Of High Power Semiconductor Devices", Robin E Hamilton et al, filed on July 22, 1996; and

U.S. patent application Serial No. 08/681,344, (58,811) entitled, "Closed Loop Liquid Cooling Within RF Modules", Robin E. Hamilton et al, filed on July 22, 1996.

BACKGROUND OF THE INVENTION

Technical Field

The present invention relates to devices, and the methods embodied therein, for liquid cooling of circuit board assemblies. More particularly, the liquid for cooling the circuit board assembly is pumped via a non-mechanical, magnetic pump.

Description of the Prior Art

It is known that an electric current can be used to pump an electrically conductive fluid without the use of moving parts. United States Patent No. 2,612,109 discloses such a magnetic, non-mechanical pump that is to be fitted around an electrically conductive pipe.

In an unrelated technological area, for at least the last 20 years, the electronics industry has

demanded solid-state switching devices that operate faster, handle more power, are smaller, and cost less. The semiconductor industry has responded with the advent of such devices as MOSFETs and insulated gate bipolar transistors (IGBTs). These devices have offered tremendous advancements in such applications as power supplies and motor controllers. Densely packaged, low cost devices that handle kilowatts of power have been developed. These devices, however, are still limited internally by power density and thermal considerations.

From a reliability perspective, the electronics industry has gravitated toward air cooled devices. For example, the Federal Aviation Administration (FAA), requires radar systems to be air cooled. Likewise, though not formally required, television broadcasters greatly prefer air cooled electronic devices.

Prior art air cooled electronic packaging frequently includes redundant parts in order to compensate for the limited capacity of air cooled designs, resulting in greater system cost, size, and weight. For example, consider the air cooled ARSR-4 solid state transmitter developed by the Westinghouse Electric Corporation. This is an example of a transmitter using radio frequency (RF) power transistors that are designed to operate below their power output capability. In addition, in order to meet military standard operating temperatures when plural ARSR-4 transistors are being used, the transistors must be spaced inches from one another, which is an inefficient use of the surface area of the circuit board assembly. In effect, the number of transistors and related peripheral circuits that are required in a solid state transmitter is a function of

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the thermal capacities of the prior art transistor
packaging and air cooling systems.

The ARSR-4 packaging approach has been
embraced by the industry for several years due to its
5　　simplicity, low cost, and customer acceptance. Figure
1 depicts the prior art ARSR-4 air cooled RF module
along with a thermal model thereof. The ARSR-4 module
8 includes: a transistor chip 10; a ceramic layer 12;
a flange 14; a soft substrate 16; a ground plane 18;
10　　a cold plate 20; fins 22; and arrows 24 representing
air flow. Items 10, 12 and 14 form the transistor,
items 16 and 18 form the bare circuit board, and items
20 and 22 form the coldplate.

The thermal model in Figure 1 shows that the
15　　prior art packaging, along with the maximum air flow
that can be realized, limit the maximum heat
dissipation of an air cooled silicon RF transistor to
about 10 Watts. The maximum device junction
temperature, T, as dictated by system reliability
20　　studies, is usually desired to be in a range $125°C \leq$
$T \leq 135°C$. Technological advancements in high power
transistor designs have begun to exceed the cooling
capacity of the prior art air cooled designs.

Further enhancements to improve the thermal
25　　efficiency of prior art air-cooled designs are
difficult in practice. Increasing the mass flow rate
of air over a module is difficult. For example, the
ARSR-4 transmitter generates over 12 kilowatts average
heat dissipation. The blower used to cool this very
30　　large system is 20 hp, rated to deliver approximately
10,000 cubic feet per minute of air at 8 inches of
water pressure drop. This blower is excessively
large, expensive, and noisy. Alternatively, the
thermal interface between the transistor flange 14 and
35　　the substrate-16/ground plane-18 can be improved with

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solder. Unfortunately, this adds considerable costs in module rework.

Liquid cooling, in contrast, provides greater heat dissipation capacity. Nevertheless, as discussed above, many end users have strong objections to liquid cooling. Liquid cooling is perceived as expensive and heavy, having reduced reliability, and excessive maintenance problems due to leaks, fouling, and corrosion. In addition, many applications simply do not have liquid cooling available.

Conventional Art

In the above referenced related copending patent applications assigned to the same assignee as the present application, liquid cooling has been applied to circuit board assemblies to enhance the power density capabilities thereof. In particular, this new approach to liquid cooling is based upon the concept of microchannels. Microchannel cooling forces dense fluids through very small channels located as close as possible to the heat source. Typically, cooling channels are embedded either within the circuit board itself and/or within the substrate of the electronic device. A typical microchannel is sized as follows: 25 μm wide; 1.5 μm deep; and 7.1 μm long.

The preferred embodiments of the microchannel technology keep the fluid-path entirely on a circuit board assembly. As such, no fluid connections need be severed in order for the circuit board to be removed for repair or replacement. This enhances the reliability of this liquid cooled technology.

A pump, residing on the circuit board assembly, becomes desirable to circulate the coolant in the microchannel. From a reliability perspective,

a device having moving parts, such as a pump, is a liability because, generally, devices with moving parts are less reliable than devices having no moving parts. Thus, there exists a need for a pump, small enough to fit on a circuit board assembly, that can pump the coolant through the microchannel without employing moving parts.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a liquid cooling system for a circuit board assembly that is completely contained on that circuit board assembly.

It is a further object of the present invention that the liquid cooling system employ microchannels.

Here is a further object of the present invention that the coolant of the liquid cooling system be pumped by a non-mechanical pump.

These and other objects of the present invention are fulfilled by providing a method of cooling a device having a liquid cooling system, the method including: using an electrically conductive fluid as the coolant; and using the fluid to conduct at least a portion of the electricity flowing in an electrical current path. This method further includes inducing a magnetic field orthogonal to a direction that the electricity flows and orthogonal to a direction of fluid flow, to thereby pump the fluid in the system via a resulting non-mechanical, Lorentz force.

Such objects of the present invention are also fulfilled by providing a liquid cooling system resident on a circuit board assembly, and the method embodied therein, comprising: a circuit board, a cooling channel, having a channel wall located within

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the circuit board; coolant filling the channel; and a non-mechanical pump having a fluid connection to the channel, for circulating the fluid within the channel. The liquid cooling system further includes an
5   electrical power source supplying electric power along an electrical current path. The coolant is electrically conductive fluid. The non-mechanical pump is partially formed as a section of the channel. At least a portion of the channel wall in the pump
10   section of the channel is electrically conductive. The electrically conductive portion of the channel wall is electrically connected to the electrical current path, such that the fluid and the electrically conductive channel wall portion together form part of
15   the electrical path and electric current flows across the channel orthogonal to a direction of fluid flow in the channel. The non-mechanical pump includes a magnetic field source inducing a magnetic field orthogonal to each of the direction of the fluid flow
20   in the channel and the direction of the electrical current across the channel. The orthogonal orientation between the magnetic field and the electrical current exerts an orthogonal Lorentz force on the fluid as a function of a cross product of the
25   electrical current and the magnetic field. As such, the orthogonal Lorentz force pumps the fluid along the channel. The pumped fluid cools, via conduction, a proximate device.

Such objects of the present invention are
30   also fulfilled by providing an integrated semiconductor device and non-mechanical magnetic pump, and the method embodied therein. The semiconductor device includes at least a first layer of semiconductor material deposited against a second
35   layer of semiconductor material to form a junction.

This integrated system includes: a channel within the first layer of semiconductor material; a magnetic field source inducing a magnetic field within, and perpendicular to, a thickness of the first layer; and

5   an electrically conductive fluid within the channel. The electric current, for energizing the semiconductor device, is transmitted through the first layer parallel to the thickness of the layer. The fluid in the channel conducts a portion of the current. The

10   current is orthogonal to the magnetic field such that an orthogonal Lorentz force is exerted on the fluid as a function of a cross product of the electrical current and the magnetic field.   As such, the orthogonal Lorentz force pumps the fluid along the

15   channel thereby cooling the junction.

Further scope of applicability of the present invention will become apparent from the detailed description given hereafter.   However, it should be understood that the detailed description and

20   specific   examples,   while   indicating   preferred embodiments of the invention, are given by way of illustration   only,   because   various   changes   and modifications within the spirit and scope of the invention will become apparent to those skilled in the

25   art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are

30   given by way of illustration only, and thus are not limited of the present invention and wherein ...

Figure 1 is a diagrammatic depiction of the prior art ARSR-4 solid state transmitter and a thermal model therefore;

Figure 2 is a block-level diagrammatic depiction of the liquid cooling system, for a circuit board assembly, of the present application;

Figure 3 is a cross-sectional view of the liquid cooling system, for a circuit board assembly, of the present application;

Figure 4 is an exploded view of the liquid cooling system, for a circuit board assembly, of the present application;

Figure 5 is an exploded view of the microchannels formed in, and the electronic devices attached to, the circuit board for the liquid cooling system of the present application;

Figure 6 is an exploded view of the non-mechanical, Lorentz force pump of the present application;

Figure 7 is a circuit diagram of the non-mechanical, Lorentz force pump of the present application;

Figure 8 is a thermal flowchart of the liquid cooling system of the present application;

Figure 9 is a cross-sectional view of the integrated semiconductor device and non-mechanical, magnetic Lorentz force pump of the present application; and

Figure 10 is a diagrammatic depiction relating the shape of the microchannel to the components of the Lorentz force.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 2 is a diagrammatic depiction of a liquid cooling system embodiment of the present application, residing completely on a circuit board assembly. Such a circuit board assembly is referred to as the module 50. The module 50 includes: the load/heat sink 52; the fluid connection 54; the heat

exchanger 56; the fluid connection 60; the non-mechanical magnetic pump 62; and the fluid connection 64. In addition, a fan 58 is depicted for forcing air past the heat exchanger 56.

5   The non-mechanical, magnetic pump 62 circulates coolant to the load/heat sink 52 via the fluid connection 64. The coolant absorbs heat energy from the load/heat sink 52 by conduction on its way to the heat exchanger 56 via the fluid connection 54. At
10   the heat exchanger 56, heat energy is transferred from the coolant to the air adjacent the circuit board assembly by convection. The fan 58, which is not a necessary component, moves air past the heat exchanger 56. The now-cooled coolant is circulated back to the
15   pump 62 via the fluid connection 60.

Figure 3 is a cross-sectional view of the module 50 of Figure 2. The module 50 includes: a semiconductor device, for example, a transistor chip, 100; a ceramic layer 102; a flange 104; a soft
20   substrate 106; a ground plane/air to liquid heat exchanger 108; fins 110; arrows depicting airflow 112; a non-mechanical, magnetic pump 114; coolant 116; and a channel 118 in which the coolant 116 flows.

The module 50 of Figure 3 represents a
25   packaging approach which achieves the simplicity of air cooling, something mandated by the user, while providing the thermal efficiency of a liquid cooling system. This module 50 is a closed loop in the sense that the entire fluid circuit is contained on the
30   circuit board assembly. As such, when a module 50 is replaced, no plumbing is involved, i.e., no fluid connection must be broken. The printed wiring board 106, 108, and 110 doubles as an air-to-liquid heat exchanger.

Figure 4 depicts an exploded view of an alternative embodiment of the module 50, namely, the module 150. The module 150 includes: a circuit board 151; semiconductor devices, for example, power transistors or motor controllers, 152; a non-mechanical, magnetic pump 154; a fluid connection, i.e., a channel 156; coolant 116; a check valve 158; a fill port/vent 160; a channel 162; a liquid to air heat exchanger 164; fins 166; and a check valve 168.

Figure 4 corresponds to the common situation in which the module 150 has one transistor 152 that drives four other transistors 152. A single non-mechanical, magnetic pump 154 circulates fluid in the channel portions 156, and 162 to cool a total of five transistors 152. This is in contrast to the one pump 114 to the one transistor chip 100 ratio depicted in Figure 3. Figure 4 also shows that the channel portion 162 has a serpentine arrangement, thereby increasing the overall length or effective size of the heat exchanger 164.

Figure 5 depicts a cross-section of an alternative module 200. The module 200 includes: semiconductor devices 202, 204, and 206; a substrate 208; coolant channels 210; coolant 116; and a channel closure 212.

A microchannel heat sink, formed by the combination of the coolant channels 210 and the channel closure 212, is similar to a conventional finned heat sink, except for a fundamental difference in the dimensions. A typical microchannel is on the order of 0.001 inches wide by 0.004-0.006 inches deep.

Microchannels enhance heat transfer in two ways, first, the narrow channels can be closely spaced, giving a large number of fins with a combined surface area much greater than the "footprint" of the

heat sink.   Second, the small hydraulic diameters of the microchannels result in high convection heat transfer coefficients.

The thermal conductivity of a heat sink is proportional to the product of the convective heat transfer coefficient and the surface area. As such, microchannels allow an increase in the maximum power density for a given operating temperature.   The superior performance of a microchannel heat sinks enables minimal flow to remove heat effectively from a hot component. The reduced flow requirements enable a small capacity pump to supply adequate amounts of coolant to a heat generating device.   In addition, closed loop liquid cooling contained completely on a circuit board assembly preserves the cleanliness of the coolant, due to minimal introduction of outside impurities and debris. Such cleanliness is required of the coolant used in microchannels because of the tiny dimensions involved.

Figure 6 is an exploded view of the non-mechanical, magnetic pump 250.   The pump 250 is integrated into the channel 252 and has a conductor cross-section 254.   The channel 252 includes the channel wall 256, the channel floor 258, and the channel ceiling 260. Figure 6 also shows the magnetic field sources 262-264.

The non-mechanical, magnetic pump 250 of Figure 6 operates as follows. The Lorentz force is defined by the following equation:

$$\vec{F} = q * \vec{v} \ X \ \vec{B} \tag{1}$$

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In equation No. 1, q is the charge, $\vec{v}$ is the velocity

of the charge, $\vec{B}$ is the magnetic field in which the

charge is travelling, and $\vec{F}$ is the force on the charge

due to the cross product of the velocity and magnetic

5   field vectors.

Rewriting equation 1 in terms of the current travelling in a conductor results in the following equation:

$$\vec{F} = I * \vec{\ell} \ X \ \vec{B} \qquad\qquad (2)$$

10   In equation 2, I is the value of the current and $\vec{\ell}$ is

the length over which the current is travelling. An exemplary calculation of the magnitude of the Lorentz force follows.

With the exception of the conductor cross-
15   sections 254, the channel walls 256, as well as the channel floor 258 and the channel ceiling 260 are electrically non-conductive. All of the electrical current will travel through the coolant in the region between the two conductor cross-sections 254, in a

20   direction parallel to $\vec{\ell}$.

The coolant 116 in the channel 252 is electrically and thermally conductive. A typical average current available in a transmitter transistor circuit is one ampere. The power consumption of the
25   non-mechanical, magnetic pump 250 is minimal such that no additional power need be supplied beyond what is already available from the transistor.

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As for the magnetic field sources 262 and 264, a typical field between two commercially available neodymium-iron-boron alloy permanent magnets is 2700 Teslas. It is preferred to use two magnetic field sources whose fields combine in the region defined between the conductor cross-sections 254, but a single magnetic field source could also be used. An electromagnet could also be used as the field source.

A one inch square magnet has the following magnetic field area:

$$A_{mag} = \ell_2 * \ell_3 = 1 \; sq. \; in. \tag{3}$$

To reiterate, Figure 6 is an exploded view, thus, the magnetic field sources 262 and 264 are shown displaced from the channel 252. In a reduction to practice, the magnetic field source 262 is positioned as closely as possible against the channel ceiling 260 while the magnetic field source 264 is positioned as closely as possible against the channel floor 258. If the gap between the two magnetic field sources 262 and 264, equals .25 inches, then the gap area is defined as follows:

$$A_{gap} = (\ell_2 + h) * (\ell_3 + h) = 1.56 \; in. \tag{4}$$

The gap dimension, h, is added (in the A_{gap} calculation) to both the length ℓ_3 and the width ℓ_2 according to the well-known, empirically derived technique for compensating the effects of fringing in short gaps. This gap area is only valid for a gap length less than the length of the magnetic face. Magnetic size and gap length are chosen arbitrarily to achieve the desired size and resultant forces. Thus,

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the magnetic force across the gap is calculated as follows:

$$B_{gap} = B_{mag} * (A_{mag}/A_{gap}) = 1731 \; Teslas \qquad (5)$$

The resultant force applied to the coolant is:

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$$F = (1 \; amp) * (0.0254 \; m) * (1731 \; Teslas) = 44 \; Newtons \qquad (6)$$

The resultant pressure on the coolant is:

$$P = (44 \; N)/(0.0254 \; m * 0.00635 \; m)$$
$$= 27.3(10^4) \; N/m^2 \qquad (7)$$
$$= 39.6 \; \ell bs/in.^2$$

This pressure is adequate to move an electrically conductive fluid through a closed loop coolant path
10　contained completely on a circuit board assembly.

　　　　Figure 7 depicts a schematic representation of a module 300. The module 300 includes: a non-mechanical, magnetic pump 302; a voltage source 308; and a power transistor 310. The power line sourcing
15　the transistor 310 also sources current for the pump 302. The pump could be similarly formed into any other circuit on the board. The pump 302 includes a pump resistance R_p 304 and an electrically conductive coolant loop 306.
20　　　　　Because the fluid in the channel is electrically conductive, the entire channel is viewed as the loop 306. Nevertheless, as discussed above, electricity only flows across the region defined by the conductor cross-sections 254. The energy that is
25　transformed into work by the pump 302 is accounted for

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by the voltage drop across the pump resistance R_p, which is a relatively small resistance.

Figure 8 depicts a thermal schematic for all of the present embodiments. The arrow 352 indicates
5   heat that is input from the device that is to be cooled, e.g., a power transistor. The box 354 represents the cooling channels within which is held the electrically conductive liquid. The arrow 356 represents the work contributed by the non-mechanical,
10 magnetic pump. The arrow 358 represents heat energy being carried away from the power transistor to the heat exchanger, represented by the box 360. The arrow 362 represents heat being removed by the heat exchanger 360. The arrow 364 represents the return of
15 cooled fluid to the portion of the cooling channel prior to the portion of the cooling channel that is located proximately to the power transistor.

Figure 9 is a cross-sectional illustration of an alternative embodiment of the non-mechanical
20 magnetic pump of the present application, namely an integrated pump/semiconductor device 400. The preferred embodiment of the semiconductor device is a power transistor. The integrated pump/transistor 400 includes: a transistor emitter 402; a transistor base
25 404; a transistor collector 406; a microchannel 407 for carrying electrically conductive coolant 116; an electrically conductive sealing layer 408; fins 409; a south magnetic pole face 410; and a north magnetic pole face 412.

30 Figure 10 depicts an exemplary microchannel cross-section 450 of the microchannel 452 of the pump/transistor 400. The microchannel 452 includes: a microchannel sealing 454; microchannel walls 456; and a microchannel floor 458. The orthogonal
35 relationship of the Lorentz force cross product is

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depicted by the set of axis 460 while the set of axis 462 depict orthogonal reference axes.

In this embodiment, a separate pump is not necessary. In the microchannel 452, $\vec{\varrho}$ is the depth of

5   the microchannel. A calculation of an exemplary force magnitude follows. A typical average current available in a transmitter transistor is 1/2 ampere.

The walls 456, the ceiling 454, and the floor 458 are formed of intrinsic (i.e., undoped)

10 silicon with a resistivity of $\rho = 85 \ (10^3) \ \Omega$ cm. Using mercury as the exemplary conductive coolant with a resistivity of $\rho = 96 \ (10^{-6}) \ \Omega$ cm, essentially all of the current will travel into the depth of the microchannel 452 via the coolant 116.

15 The microchannels are so small that a transistor will have on the order of 175 microchannels etched therein. As such, for the sake of illustration, Figure 9 does not accurately represent the number of microchannels. The current density in

20 the microchannel will be:

$$J = (0.5)/(175*0.245(10^{-6})*7.1(10^{-6})) \qquad (8)$$
$$= 1.6(10^{-9}) \ Amp \ m^{-2}$$

In any single channel, the current will be:

$$\vec{I} = 2.9(10^{-3}) \ Amp \ in \ the \ (-\vec{k}) \ direction \qquad (9)$$

In other words, the current flows from the channel

25 ceiling 454 towards the channel floor 458 in a direction opposite to the reference axis $\vec{k}$. An

exemplary value of the $\vec{B}$ at a distance of 1 cm from

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the pole face of the exemplary neodymium-iron-boron alloy permanent magnet is 1 tesla (Weber/m^2). The $\vec{\ell}$ is 1.5(10^{-6}) meters in the $\vec{-k}$ direction. The force in each microchannel on the coolant is

$$\begin{bmatrix} \vec{F} = 0.0029*(1.5(10^{-6})*1)\,(\vec{-k}\;X\;\vec{-j}) \\ = 4.4(10^{-9})\;Newtons\;in\;(\vec{-i}\;)\;direction \end{bmatrix} \quad (10)$$

Recalling that pressure is equal to the force divided by the area, this corresponds to 11,400 pascals (Newtons/m^2) on the coolant or 1.6 pounds force per square inch, an adequate pressure to pump an electrically conductive fluid such as mercury through the microchannels 407.

While mercury is the most well-known electrically conductive fluid, there are others that can be used. Other substances that are a liquid at the temperatures at which a power transistor, for example, would operate include Cesium (having a resistivity of ρ = 36.6(10^{-6}) Ω cm), Gallium (having a resistivity ρ 27(10^{-6}) Ω cm), and a Sodium-Potassium 50/50 alloy (having a resistivity $\rho \approx$ 10(10^{-6}) Ω cm and having a melting point of 11°C). Another element, Bromine, is not suitable because it boils at 59°C.

Of these conductors, the 50/50 Na-K alloy is preferred because it has a high thermal conductivity, about 1 watt/(cm C°), which is more than ten times higher than mercury. Also, the 50/50 Na-K alloy has a specific heat of approximately 0.2 calories/(gram C°).

The embodiments of the present application employ a non-mechanical magnetic pump to move

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electrically conductive fluid through a fluid path
contained completely on a circuit board assembly. In
particular, the fluid path is a microchannel. In some
of the embodiments, the device to be cooled is
5   integrated with the pump itself while in others the
pump is separated from the devices to be cooled.

The non-mechanical, magnetic pump uses a
strong, permanent magnet inducing a field orthogonal
to the direction of a high current in order to
10   generate a Lorentz force that moves the electrically
conductive fluid. Such a completely intra-circuit-
board-assembly liquid cooling system provides the
simplicity of air cooling mandated by end users of
such circuit boards while achieving the thermal
15   efficiency of a liquid system. A transmitter that
employs such a cooling system can extract higher power
levels from existing circuit designs than if these
circuit boards were cooled only by air. In the
alternative, fewer components can be placed on a
20   circuit board and yet still achieve the same
performance. This minimizes the parts count for the
circuit board assembly, which results in enhanced
reliability, and reductions in the system cost, size
and weight.

25   To reiterate the advantages of the present
application, a mechanical pump, i.e., one having
moving parts, is eliminated. The use of microchannels
permits a much smaller capacity pump, such as the non-
mechanical magnetic pump, to satisfy the circulation
30   needs of the cooling system. Because the cooling
system can fit entirely on a circuit board assembly,
the entire cooling system can be permanently sealed.

The invention being thus described, it would
be obvious that the same may be varied in many ways.
35   Such variations are not to be regarded as a departure

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from the spirit and scope of the invention, in all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

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I claim the following:

1.   A method of cooling a device having a liquid cooling system, comprising the steps of:
          a)   using an electrically conductive fluid as a coolant; and
5   b)   using the fluid to conduct at least a portion of the electricity flowing in an electrical current path.

2.   A method as in claim 1, further comprising the step of:
10   c)   inducing a magnetic field orthogonal to a direction that the electricity flows and orthogonal to a direction of fluid flow, to thereby pump the fluid in the system via a resulting non-mechanical, Lorentz force.

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3. A liquid cooling system resident on a circuit board assembly comprising:

a circuit board;

a cooling channel, having a channel wall, located within the circuit board;

coolant, filling the channel; and

a non-mechanical pump, having a fluid connection to the channel, for circulating the fluid within the channel.

4. A liquid cooling system resident on a circuit board assembly as in claim 3, further comprising:

an electrical power source supplying electric current along an electrical current path;

wherein:

the coolant is electrically conductive fluid;

the non-mechanical pump is partially formed as a section of the channel;

at least a portion of the channel wall in the pump section of the channel is electrically conductive;

the electrically conductive portion of the channel wall being electrically connected to the electrical current path, such that the fluid and the electrically conductive channel wall portion together form part of the electrical path and electric current flows across the channel orthogonal to a direction of fluid flow in the channel;

the non-mechanical pump includes:

a magnetic field source inducing a magnetic field orthogonal to each of the direction of the fluid flow in the channel and the direction of the electrical current across the channel;

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the orthogonal orientation between the magnetic field and the electrical current exerting an orthogonal Lorentz force on the fluid as a function of a cross product of the electrical current and the

5   magnetic field;

the orthogonal Lorentz force pumping the fluid along the channel.

5.   A liquid cooling system resident on a circuit board assembly as in claim 3, wherein:

10   the fluid is in a liquid state at any operating temperature of the circuit board.

6.   A liquid cooling system resident on a circuit board assembly as in claim 3, wherein:
the channel is a microchannel.

15   7.   A method of liquid cooling a circuit board assembly, including, a circuit board; a cooling channel, having a channel wall, located within the circuit board, at least a portion of the channel wall in a pump section of the channel being electrically

20   conductive; and electrically conductive coolant filling the channel, the electrically conductive portion of the channel wall being electrically connected to an electrical current path, such that the fluid and the electrically conductive portion together

25   form part of the electrical path;
the method comprising the steps of:
a)   supplying electric current along the electrical current path such that electric current flows across the channel orthogonal to a direction of

30   fluid flow in the channel; and
b)   inducing a magnetic field orthogonal to each of the direction of the fluid flow

in the channel and the direction of the electrical current across the channel;

the orthogonal orientation between the magnetic field and the electrical current exerting an orthogonal Lorentz force on the fluid as a function of a cross product of the electrical current and the magnetic field;

the orthogonal Lorentz force pumping the fluid along the channel.

8.   A method as in claim 7, further comprising the step of:

c)   selecting, prior to step a), the fluid so as to be in a liquid state at any operating temperature of the circuit board.

9.   A liquid cooling system resident on a circuit board assembly comprising:

a circuit board;

at least one device attached to the circuit board;

a cooling channel, having a channel wall, located within the circuit board and proximately to the at least one device;

coolant, filling the channel; and

a non-mechanical pump, having a fluid connection to the channel, for circulating the fluid within the channel to cool the proximately located device.

10.   A liquid cooling system resident on a circuit board assembly as in claim 9, further comprising:

an electrical power source supplying electric current along an electrical current path;

wherein:

the coolant is electrically conductive fluid;

the non-mechanical pump is partially formed as a section of the channel;

at least a portion of the channel wall in the pump section of the channel is electrically conductive;

the electrically conductive portion of the channel wall being electrically connected to the electrical current path, such that the fluid and the electrically conductive channel wall portion together form part of the electrical path and electric current flows across the channel orthogonal to a direction of fluid flow in the channel;

the non-mechanical pump includes:

a magnetic field source inducing a magnetic field orthogonal to each of the direction of the fluid flow in the channel and the direction of the electrical current across the channel;

the orthogonal orientation between the magnetic field and the electrical current exerting an orthogonal Lorentz force on the fluid as a function of a cross product of the electrical current and the magnetic field;

the orthogonal Lorentz force pumping the fluid along the channel.

11. A liquid cooling system resident on a circuit board assembly as in claim 9, wherein:

the fluid is one of mercury, cesium, gallium, and a sodium-potassium alloy.

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12.   A liquid cooling system resident on a circuit board assembly as in claim 9, wherein:
the magnetic field source is at least one permanent magnet.

5   13.   A liquid cooling system resident on a circuit board assembly as in claim 12, wherein:
the permanent magnet is formed at least in part from a rare earth element.

14.   A liquid cooling system resident on a
10   circuit board assembly as in claim 9, wherein:
the at least one permanent magnet is a neodymium-iron-boron alloy.

15.   A liquid cooling system resident on a circuit board assembly as in claim 9, wherein:
15   the at least one device draws power from the electrical current path, the electrical power source thereby sourcing the non-mechanical pump and the at least one electrical device.

16.   A liquid cooling system resident on a
20   circuit board assembly as in claim 9, further comprising:
heat exchanger means, attached to the circuit board and located proximately to the channel, for transferring via conduction heat from the fluid in
25   the channel to ambient air adjacent the circuit board via convection, such that fluid approaching the heat exchanger means is of a higher temperature than fluid moving away therefrom.

17.   A liquid cooling system resident on a
30   circuit board assembly as in claim 9, wherein:

the channel has a rectangular cross section.

18.   A liquid cooling system resident on a circuit board assembly as in claim 9, further comprising:

a selectively sealable port, connected to the channel.

19.   A liquid cooling system resident on a circuit board assembly as in claim 9, further comprising:

at least one check valve, connected as part of the channel.

20.   A liquid cooling system resident on a circuit board assembly as in claim 9, wherein:

the channel is a microchannel.

21.   A liquid cooling system resident on a circuit board assembly as in claim 9, wherein:

a first and second magnetic field source aligned so that a field from each is induced within, and perpendicular to a thickness of, the first layer, the two magnetic fields combining within the first layer.

22.   A liquid cooling system resident on a circuit board assembly as in claim 21, wherein:

each of the two magnetic field sources are permanent magnets having north and south poles, the south pole of the first magnet being aligned with the north pole of the second magnet to produce the magnetic field combination.

23.   A liquid cooling system resident on a circuit board assembly as in claim 9, wherein:

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the at least one electrical device is a power transistor.

24. A liquid cooling system resident on a circuit board assembly as in claim 23, further comprising:

five power transistors.

25. A liquid cooling system resided on a circuit board assembly as in claim 9, wherein:

the at least one electrical device is a motor controller.

26. A liquid cooling system resident on a circuit board assembly as in claim 9, further comprising:

a separate channel, fluid, and non-mechanical pump for each of five power transistors.

27. A liquid cooling system as in claim 9, wherein:

the electronic device is a semiconductor device including at least a first layer of semiconductor material deposited against a second layer of semiconductor material to form a junction;

a portion of the channel is formed within the first layer of semiconductor material such that the non-mechanical pump is integrated with the semiconductor device;

the non-mechanical pump including:

a magnetic field source inducing a magnetic field within, and perpendicular to a thickness of, the first layer;

the coolant is an electrically conductive fluid;

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an electrical current that energizes the semiconductor device is transmitted through the first layer parallel to the thickness of the layer;

the fluid in the channel conducts a
5   portion of the electrical current;

the energizing current being orthogonal to the magnetic field such that an orthogonal Lorentz force is exerted on the fluid as a function of a cross product of the electrical current and the magnetic
10 field;

the orthogonal Lorentz force pumping the fluid along the channel, the pumped fluid cooling the junction.

28.   A method of using an electric current
15 flowing through a semiconductor device to non-mechanically pump cooling fluid, the semiconductor device including at least a first layer of semiconductor material deposited against a second layer of semiconductor material to form a junction,
20 the first layer having a channel therein filled with electrically conductive fluid, the method comprising the steps of:

a)   inducing a magnetic field within, and perpendicular to a thickness of, the first layer; and
25 b)   transmitting an electric current through the first layer parallel to the thickness of the layer and orthogonal to the magnetic field;

the fluid in the channel conducting a portion of the current;
30 an orthogonal Lorentz force being exerted on the fluid as a function of a cross product of the electrical current and the magnetic field;

the orthogonal Lorentz force pumping the fluid along the channel, the pumped fluid cooling the junction.

29. A method as in claim 28, wherein:
the semiconductor device is a power transistor.

30. A method as in claim 29, wherein:
the power transistor has a base, emitter, and collector;
the first layer being the collector.

31. A method as in claim 28, wherein:
the step a) of inducing involves using at least one permanent magnet.

32. A method as in claim 28, wherein:
the step a) of inducing involves:
a1) using at least a first and second magnetic field source; and
a2) aligning the first and second magnetic field source so that a field from each is induced within, and perpendicular to a thickness of, the first layer, and so that the two magnetic fields combine within the first layer.

33. A method as in claim 32, wherein:
each of the two magnetic field sources are permanent magnets having north and south poles; and
step a2) includes aligning the south pole of the first magnet being aligned with the north pole of the second magnet to produce the combined field.

34.   A method as in claim 28, further comprising the step of:

c)   transferring heat, via conduction, from the fluid in the channel to ambient air proximate to the first layer, via convection.

35.   An integrated semiconductor device and non-mechanical magnetic pump cooling system, the semiconductor device including at least a first layer of semiconductor material deposited against a second layer of semiconductor material to form a junction, the system comprising:

a channel within the first layer of semiconductor material;

a magnetic field source inducing a magnetic field within, and perpendicular to, a thickness of the first layer; and

an electrically conductive fluid within the channel;

an electric current, for energizing the semiconductor device, being transmitted through the first layer parallel to the thickness of the layer;

the fluid in the channel conducting a portion of the current;

the current being orthogonal to the magnetic field such that an orthogonal Lorentz force is exerted on the fluid as a function of a cross product of the electrical current and the magnetic field;

the orthogonal Lorentz force pumping the fluid along the channel, the pumped fluid cooling the junction.

36.   A system as in claim 35, wherein:

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the channel is a closed loop contained within a circuit card assembly.

37.   A system as in claim 35, wherein:
the magnetic field source is at least one permanent magnet.

38.   A system as in claim 37, wherein:
the permanent magnet is formed at least in part from a rare earth element.

39.   A system as in claim 38, wherein:
the at least one permanent magnet is a neodymium-iron-boron alloy.

40.   A system as in claim 35, wherein:
the solid state device is a power transistor.

41.   A system as in claim 35, wherein:
the power transistor has a base, emitter, and collector;
the first layer being the collector.

42.   A system as in claim 35, wherein:
the fluid is one of mercury, cesium, gallium, and a sodium-potassium alloy.

43.   A system as in claim 35, further comprising:
a first and second magnetic field source arranged so that a field from each is induced within, and perpendicular to a thickness of, the first layer, the two magnetic fields being aligned so as to combine within the first layer.

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44.   A system as in claim 43, wherein:
each of the two magnetic field sources are permanent magnets having north and south poles, the south pole of the first magnet being aligned with the north pole of the second magnet to produce the combined field.

45.   A system as in claim 35, further comprising:
heat exchanger means, thermally connected to the first layer, for transferring heat via conduction from the fluid in the channel to ambient air adjacent the circuit board via convection, such that fluid approaching the heat exchanger means is of a higher temperature than fluid moving away therefrom.

46.   A system as in claim 35, wherein:
the fluid is one of mercury, cesium, gallium, and a sodium-potassium alloy.

47.   A system as in claim 35, wherein:
the channel is a microchannel.

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FIG.1
PRIOR ART

10 WATTS HEAT

JUNCTION TEMP= 125°C

$\Delta T_{IC} = 45°C$

$\Delta T_{INTERFACE} = 4.4°C$

$\Delta T_{AIR-METAL} = 15.6°C$

$\Delta T_{AIR} = 8.5°C$

AMBIENT=52°C

AIRFLOW

FIG.2

LOAD/ HEAT SINK

FAN

FIG.3

FIG.4

FIG.5

FIG.6

4/5

308
+V

302
PUMP

300

304
R_p

306

310
POWER
TRANSISTOR

FIG.7

350

HEAT INPUT FROM
POWER TRANSISTOR

352   354

COOLING CHANNELS
WITH ELECTRICALLY
CONDUCTIVE LIQUID

356   WORK FROM
ELECTROMAGNETIC
PUMP

358   LIQUID
CARRYING
HEAT

HEAT REMOVED

HEAT EXCHANGER   362

360

364

FLUID RETURN
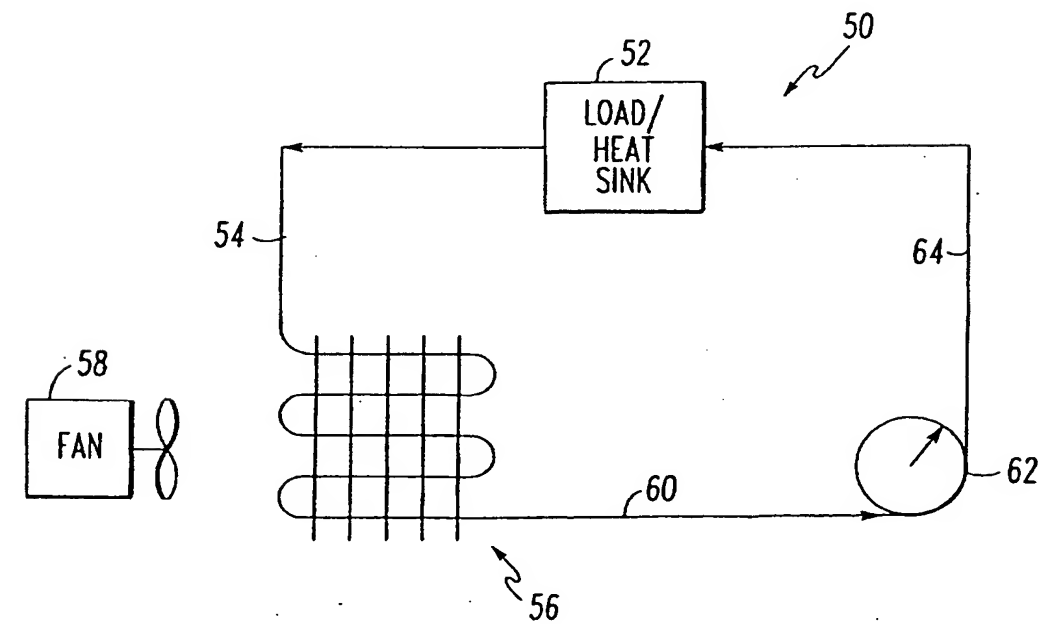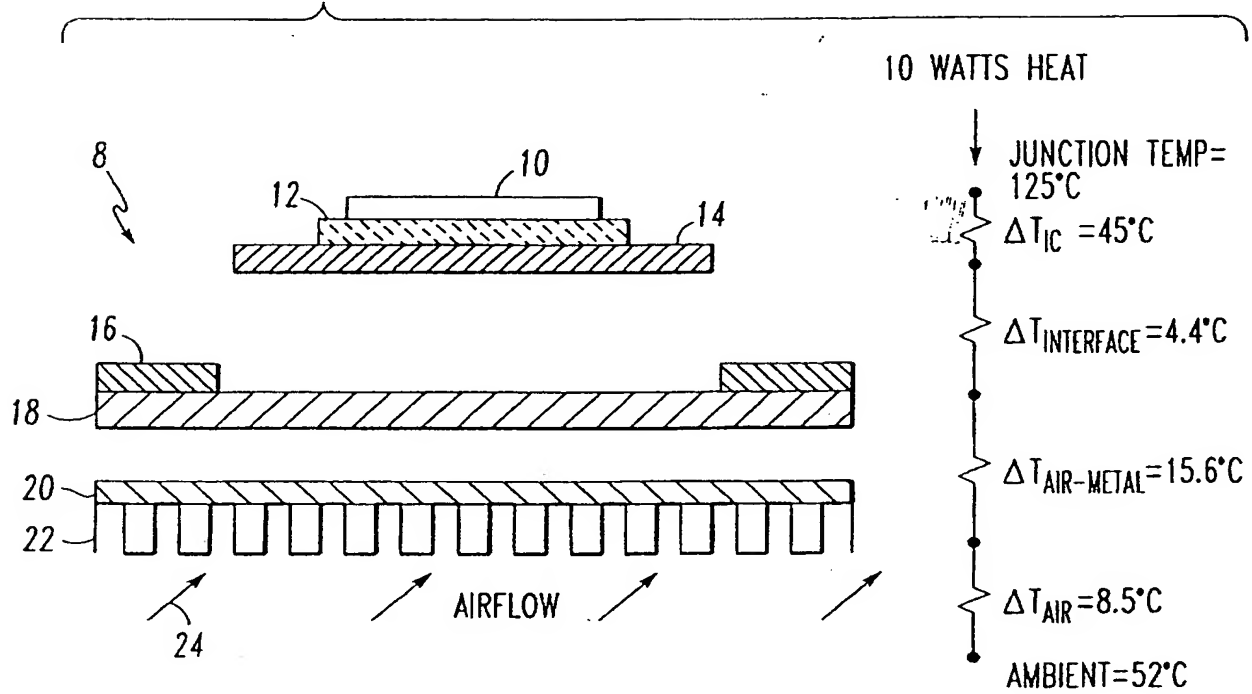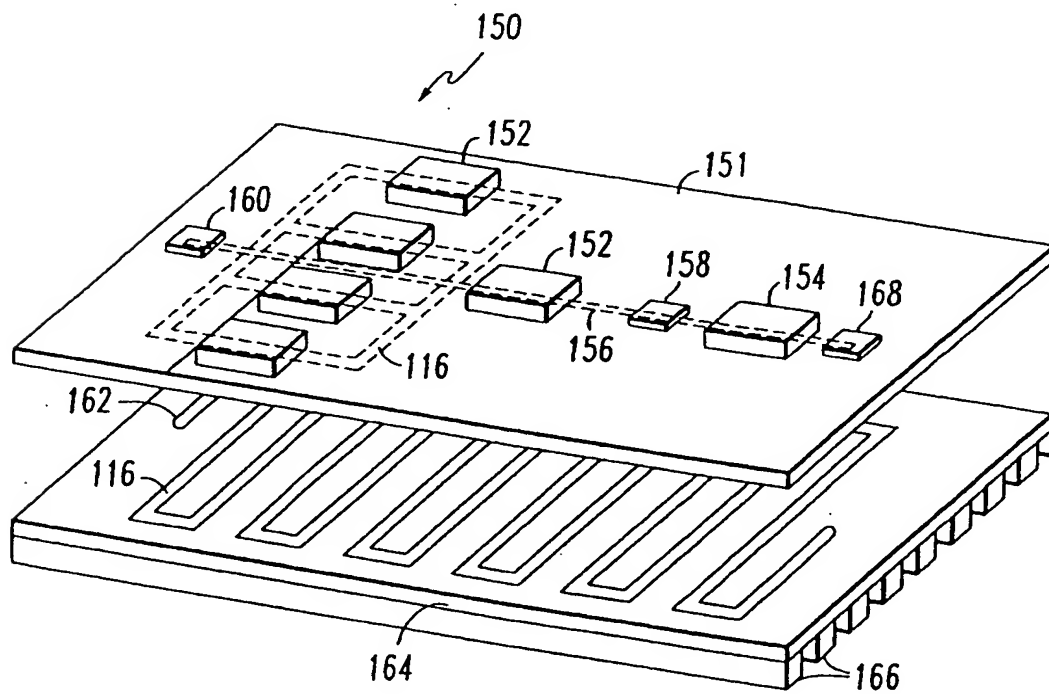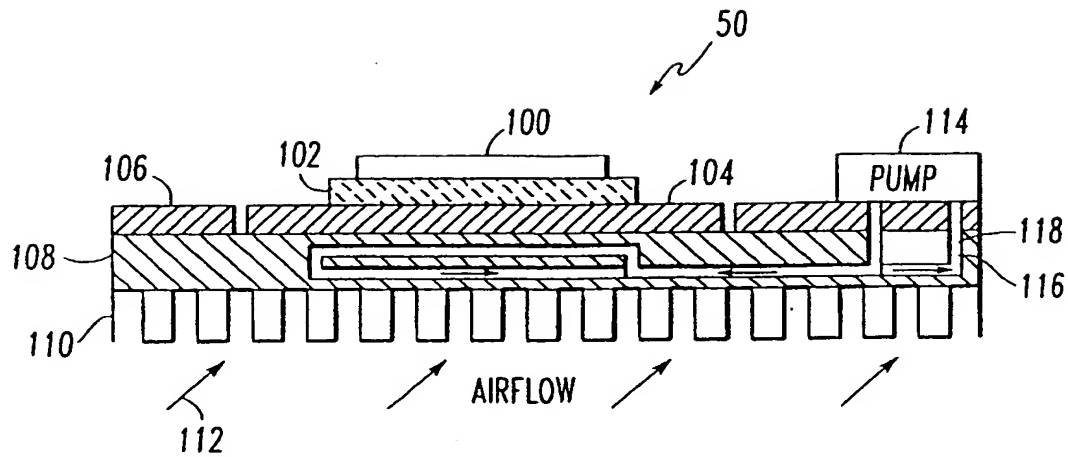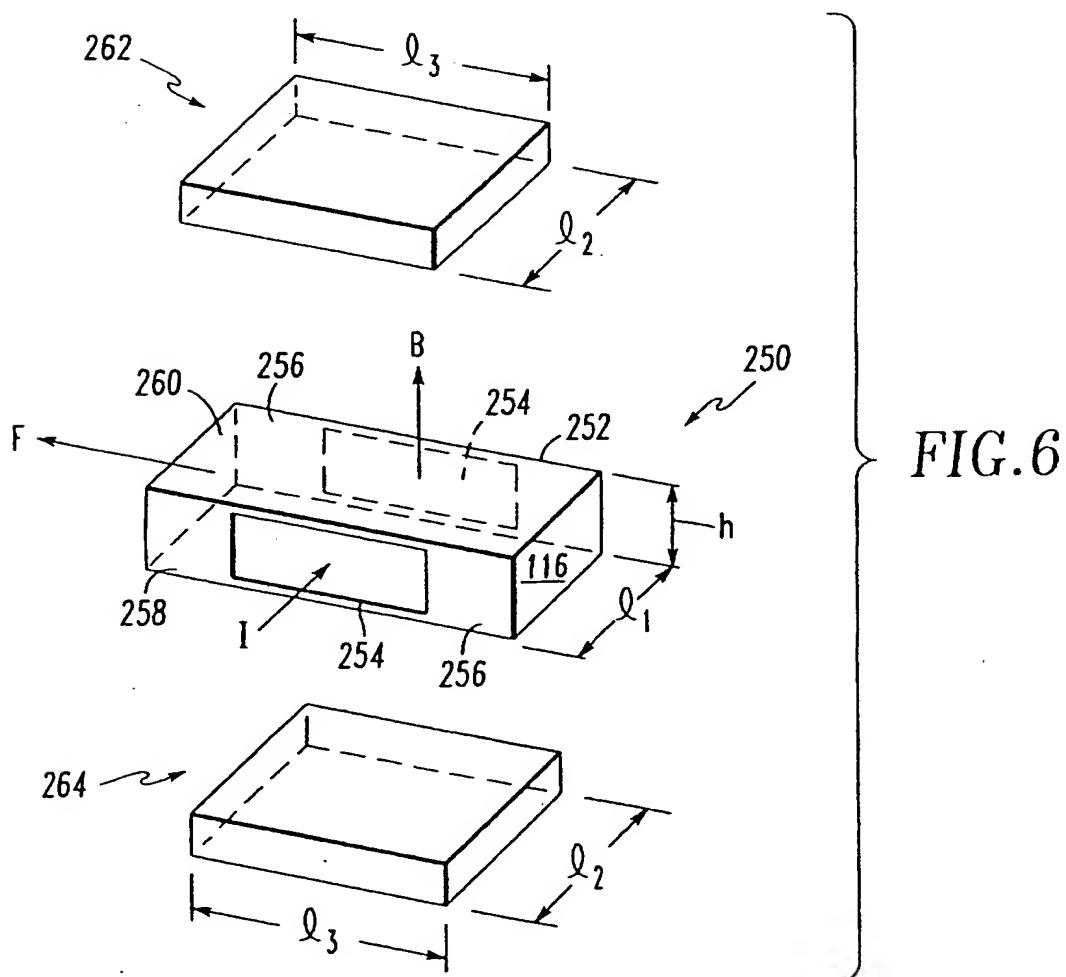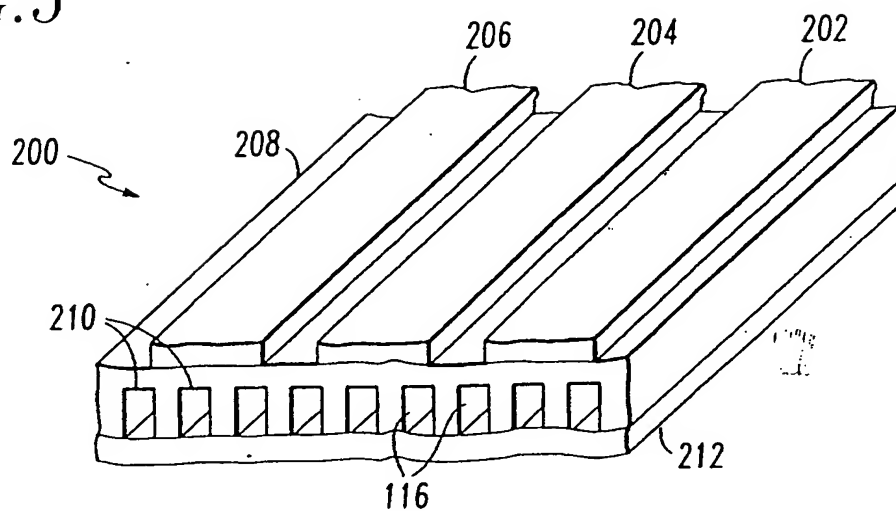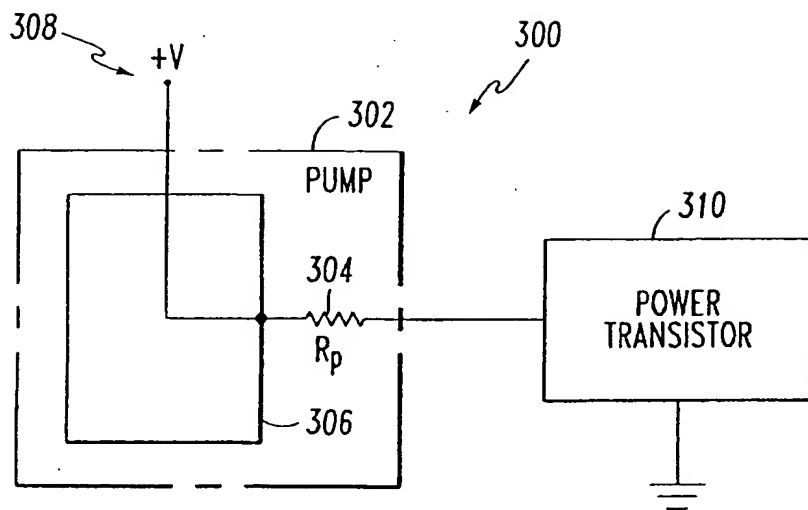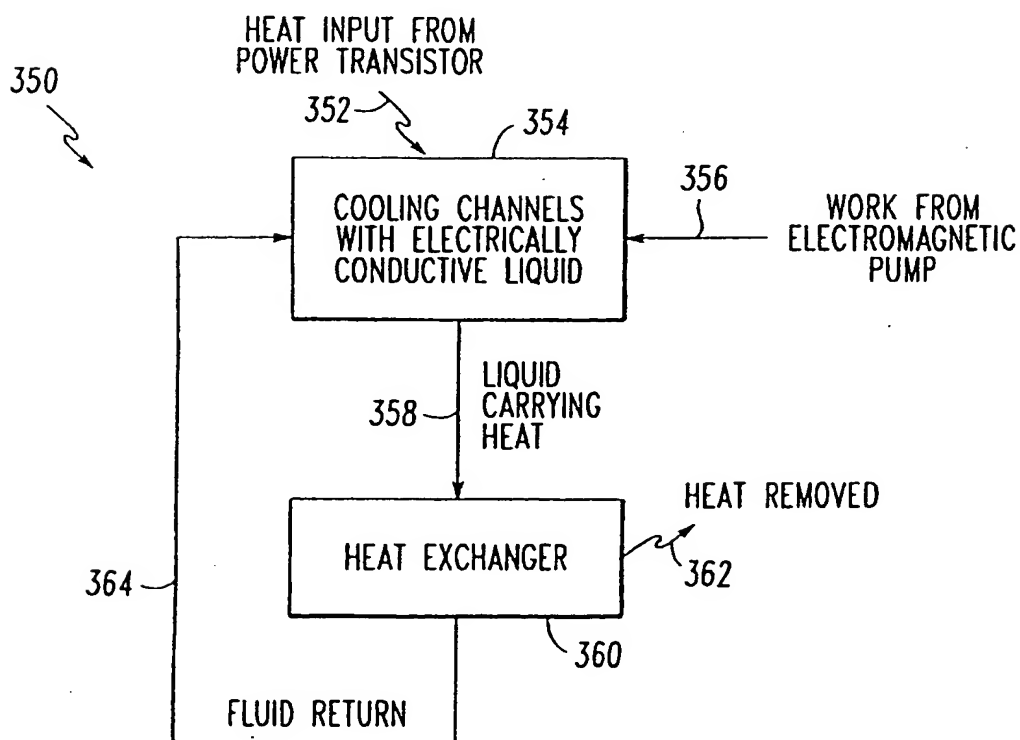
FIG.8
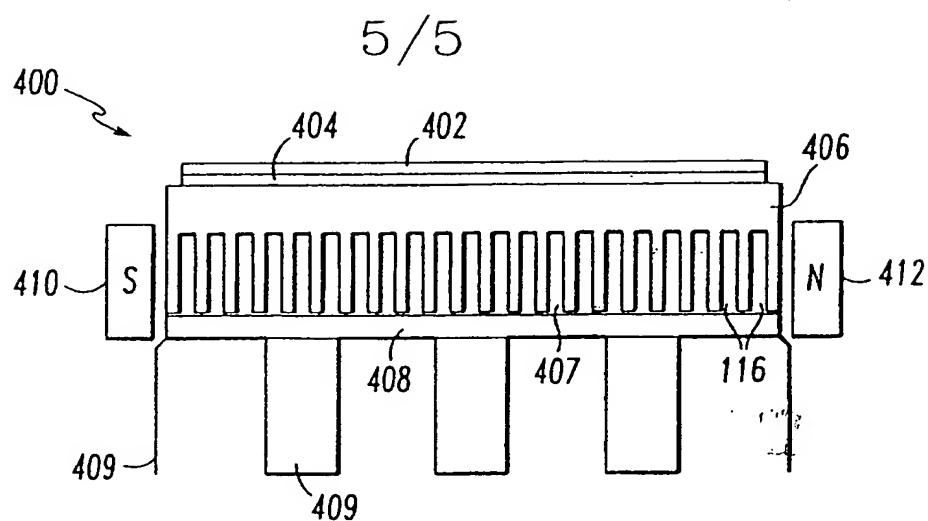
FIG.9

FIG.10

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   H05K7/20   H01L23/473

According to International Patent Classification(IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6   H05K   H01L   H02K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y A	US 4 519 447 A (WIECH JR) 28 May 1985 see the whole document --- -/--	1-6 7-9,11, 12,15, 20,27, 28,31, 35,37, 42,43, 46,47 10,13, 14, 16-19, 21-26, 29,30, 32-34, 36, 38-41,44

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

Date of the actual completion of the international search	Date of mailing of the international search report
24 October 1997	10/11/1997

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1

INTERNATIONAL SEARCH REPORT

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
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Y	see the whole document	7-9,11, 12,15, 20,27, 28,31, 35,37, 42,43, 46,47
A	U.P HWANG AND J H SEELY: "Electronic Equipment Cooling Using MHD Flow of Coolant. August 1969." IBM TECHNICAL DISCLOSURE BULLETIN, vol. 12, no. 3, August 1969, NEW YORK, US, pages 386-387, XP002044544 see the whole document	16,45
A	US 2 612 109 A (K E WAKEFIELD) 30 September 1952 cited in the application see the whole document	1,3,7,9, 28,35

INTERNATIONAL SEARCH REPORT

Information on patent family members

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US 2612109 A	30-09-52	NONE	